White Paper

Common Methodology and Resources for the Validation and Improvement of Trajectory Prediction Capabilities

− A Proposed Plan for Action −

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EXECUTIVE SUMMARY

Many Air Traffic Management (ATM) decision support tools are being deployed, or are nearing deployment, across the US and Europe. Trajectory prediction is fundamental to these tools, and the validation and improvement of trajectory predictors lie on the critical paths to their deployment.

The primary purpose of this action plan is to minimize duplication of effort in the many organisations involved in tool and predictor development, thereby reducing costs, reducing time to deployment, and enhancing the quality of the validation and improvement process.

Advanced tools are in the research phase. These tools are expected to make more exacting demands of trajectory predictors, particularly in terms of speed of computation and accuracy. Another purpose of this action plan is to understand and push the limits of trajectory predictor performance.

Execution of the action plan will create a common methodology and resources for the validation and improvement of trajectory prediction capabilities.

We ask the R&D committee to support this plan and encourage its implementation by stakeholders within the European and US ATM communities.

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Introduction

The Air Traffic Management (ATM) systems within the European Union and US are complex, dynamic, information-driven systems based on a human-centred automation paradigm. The human operators of these ATM systems make decisions based on information produced, in large part, by machines. Trajectory Prediction (TP) is a critical component of this information.

Current ATM modernization programs are deploying automation systems and Decision Support Tools (DSTs), each with their own uniquely designed and integrated TP capabilities. Given differences in design, even with the same data, each TP module may yield different trajectory predictions with different levels of computational effort. Independent efforts to date have been advantageous in that they have enabled fast parallel progress. For current operational applications, the ATM community has enjoyed success in deployment and operational use of the current generation of DST automation capabilities across many Air Traffic Service Providers (ATSPs).

Going forward, TP performance will be even more critical to meeting the requirements of future ATM DST clients. The deployment of new DST capabilities could increase the number of TP modules that are deployed. For future operational applications, this situation may present ATM stakeholders with several potential concerns that must be assessed. First is the interoperability of the overlapping TP information (i.e., do operationally significant differences in results exist?). The concern here is that any one controller could potentially be provided with complementary and/or overlapping information generated from multiple TP modules. Second, although current TP technology appears sufficient to support the first generation of Basic DST applications, evidence suggests[1] that the performance of current TP capabilities may not be sufficient to support more advanced automation applications. Third is the cost of research, development, deployment, and maintenance of multiple supporting TP modules that are similar if not overlapping. Fourth is the issue of developing cost-effective accuracy improvements and requirements for data dissemination (e.g. adaptation data in suitable formats, aircraft performance data, etc.) to provide a desired level of system performance.

Very little objective data exists within the community's literature to help stakeholders answer these critical and potentially costly questions. Individual automation projects must bear the burden to develop and validate their own TP capabilities. If the practice of independent efforts continue, progress may slow and become more costly because of duplication and resource limitations. This paper proposes a community effort to collaborate on the development and validation of common TP-supporting technologies and information. It is felt that this approach will reduce the cost of DST R&D, improve quality and interoperability, while freeing up individual stakeholders to focus their efforts, resources, and expertise on the unique features of their DST technologies.

In this paper we focus on Trajectory Prediction (TP) capabilities and how they are integrated in the ATM system in support of DST automation clients. We propose a 9-point R&D action plan to support the assessment and improvement of Trajectory Prediction capabilities in an objective "platform independent" way. By providing this capability, future system developers will have the information necessary to determine the impact of TP choices on system performance. Such decisions involve: assessments of TP speed/accuracy requirements to achieve desired DST performance, or the requirements for information accuracy, timeliness and availability to support the TP performance required for a particular DST application. Furthermore, results of this action plan will facilitate the provision of uncertainty information accompanying a trajectory-prediction product, potentially providing benefits in traffic flow management (TFM) applications.

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[1] "*Operational Requirements for Trajectory Prediction for EATCHIP Phase III*", Eurocontrol Doc. OPR.ET1.ST03.1000-ORD-02-00

European
TP topics
of interest

Joint R&D opportunities
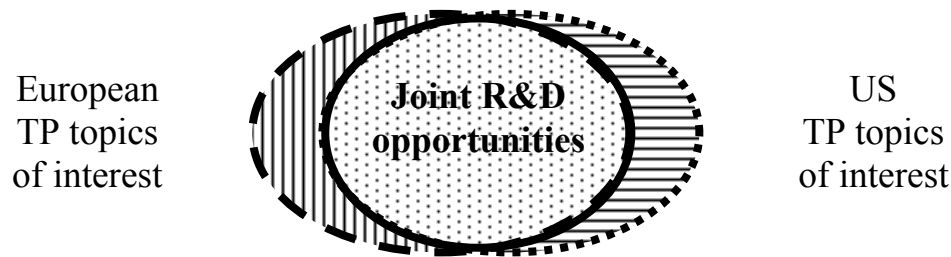
US
TP topics
of interest

Figure 1 Topics of _common_ interest for TP development

The primary purpose of this action plan is to avoid duplication of effort in the many organisations involved in tool and predictor development. As is suggested in Figure 1, where different Decision Support Tools may have different requirements for TP performance, it is also evident, that quite a number of activities associated with the design, development and validation of Trajectory Predictors could be shared amongst the interested parties. In particular this will be the case for the development of common formats for adaptation and aircraft performance data, a common methodology for the validation process and validation metrics and a common set reference data. The joint development of these support activities will reduce costs and time to deployment, enhancing interoperability and the quality of the assessment and improvement process.

Trajectory prediction

The Trajectory Prediction Module predicts the future progress of individual aircraft on the basis of the current aircraft state, estimates of pilot and controller intent, expected environmental conditions and computer models of aircraft performance and procedures. The management of "uncertainty" is critical: there will always be some possible variation in the system's behaviour, so that controllers need to make decisions whilst taking account of different possibilities. Sources of uncertainty include:

- *Data errors* – incomplete, inaccurate, corrupted or untimely data available to the controllers and automation (e.g., flight plan and radar track data inputs, airspace/navigation database, and aircraft performance modelling database),
- *Modelling errors* – simplifications, omissions and uncertainty in the mathematical models used in the system and
- *Intent errors* – unpredictability of pilot and controller intent.

These sources of uncertainty depend on both the operational conditions of interest and the implementation details of the TP modules.

Theoretically, aircraft trajectories can be computed with an unlimited look-ahead time and the complete flight can be computed. However, the uncertainty in the results increases rapidly with the look-ahead time. For example, current capabilities have an uncertainty in predicted longitudinal position that grows at an average rate of 0.2 nm per minute-look-ahead-time for level, un-accelerated flight[2] [3](greater for manoeuvring situations such as those related to congested airspace where automation is needed most). Much of the error in today's systems is due to the accuracy of the intent models. Some of these errors can be resolved through more advanced data interfaces and the integration of data link with DST automation (e.g., the Downlink of Aircraft Parameters (DAP)). Furthermore, advanced automation capabilities now emerging have the potential to mitigate these intent errors through sophisticated heuristics and dynamically updated advisories to the controller that, if acceptable to the controller, provide the automation with an accurate model of flight path

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[2] Storey J., Watt A., 1991, "*Investigation into factors affecting the performance of along-track position prediction algorithm for commercial aircraft*", Eurocontrol Experimental Centre Report 240

[3] Arthur C., Willam, Dr. Michael P. McLaughlin, (1998) "*User Request Evaluation Tool (URET) Interfacility Conflict Probe Performance Assessment, 2nd USA/Europe Air Traffic Management R&D Seminar,*" December.

intent. When these emerging capabilities are combined with other advances in aircraft tracking and wind forecasting, the remaining TP error is primarily due to items we have the ability to improve such as the mathematical modelling of the trajectories and aircraft performance.

TP client applications

In the present ATM world four general classes of ground-based TP clients can be identified:[4]

1. Flight Plan Distribution and Sector Loading

The task of Flight Plan Distribution[5] *(a typical Pre-flight application)* requires the accurate prediction of the Centre Sequence (i.e., the Air Traffic Control facilities to be transited). The predictions are based on flight plan data, airspace adaptation data and average aircraft performance data.

The estimation of Sector Loading requires the prediction of the Sector Sequence and timing (i.e., the sequence of sectors to be transited and their expected time to enter each sector). The predictions are based on flight plan data, adaptation data, average aircraft performance data and meteorological data. Today, a major error source is the uncertainty in actual flight departure times. Current Traffic Flow Management (TFM) applications use a deterministic approach to sector load estimation, whereas research indicates that TFM performance can be improved by the modelling of uncertainty in the supporting trajectory prediction process.[6]

2. Flight Data Processing Systems

The estimation of hand-over conditions requires an along track prediction with a target accuracy requirement of 3-5 min. A new prediction is made if the difference between predicted and observed positions exceeds a limit value. The predictions are based on flight plan data, adaptation data (often enhanced with site specific information), meteorological data and aircraft performance data.

3. Basic Decision Support Tools

Basic Decision Support Tool (DST) capabilities have been, or are currently in the process of being deployed for operational use. Such capabilities include real-time flow control tools like the basic Arrival Management systems[7] and tools to support the sector planning function.[8] These tools monitor the flight plan and track data to advise controllers of suggested metering/sequencing and potential conflicts. Flight-path-prediction uncertainty grows with time. For conflict probe and trial planning applications, the practical time horizon for ATC use in is typically on par with the sector transit time.

4. Advanced Decision Support Tools

Advanced DSTs[9] (under development) provide added capability to directly suggest solutions (e.g., the specific ATC clearance/instructions to guide a flight through a conflict resolution). Such tools may require greater TP accuracy to support efficient planning of trajectories across multiple sectors. For example, to facilitate the efficient transition to/from the terminal area, it is required that the DST be capable of accurately predicting cruise-descent and climb-cruise profiles in the presence of tactical manoeuvres for sequencing and spacing. In effect, these tactical manoeuvres contribute a significant uncertainty in controller intent. Active advisories may mitigate this uncertainty by "closing the loop" through the provision of controller-acceptable clearance advisories. These advisories in effect provide the DST with accurate controller intent of tactical manoeuvres, which in turn contributes to the TP

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[4] Swierstra S, and Green, S., *Common Trajectory Prediction Capability for Decision Support Tools,*" paper 59, 5th US/Europe ATM R&D Seminar, Budapest, 2003.

[5] This description represents the European model. In the US, the Flight Plan Distribution and Flight Data Processing functions are integrated, and TFM is separate.

[6] Mueller K. T., Sorensen, J. A., Couluris, G. J., *"Strategic Aircraft Trajectory Prediction Uncertainty And Statistical Sector Traffic Load Modeling*," AIAA Guidance Navigation and Control Conference, August, 2002.

[7] e.g., MAESTRO, COMPASS, CALM, CTAS TMA and pFAST, etc.

[8] e.g., conflict probe functions like URET, MTCD, FACTS, CTAS D2, etc.

[9] e.g., CORA, PARR, CTAS EDA and active FAST, etc.

accuracy needed to make the advisories acceptable to the controllers. Continuous Descent Approach (CDAs) applications in the terminal are particularly sensitive to aircraft performance modelling. In general, advanced DSTs benefit strongly from improved TP performance (speed and accuracy).[3]

The challenge: definition and validation of TP performance

Although DST designers work with target performance specifications for their tools, these have not really lead to the definition of tangible and traceable performance requirements for the Trajectory Prediction function. Consequently a full top-down system design from ATM concept to the definition of minimum flight data quality is difficult if not impossible in many cases. Nevertheless it is expected that the future ATM system for many years to come, will heavily depend on the availability of reliable predicted aircraft trajectories.

On the other hand, after many years of work and significant investments, there is very little technical documentation in the literature that objectively defines the requirements for TP. Although a significant quantity of results exists for many individual applications, there are few cross-comparable results and commonly applied metrics on the actual performance of Trajectory Predictors in the literature. It is not uncommon for DST projects to simply report that their TP capabilities are qualitatively adequate and therefore "fit for the purpose."[10] This situation differs greatly from the marketing of commercial aircraft for which automation is designed to serve. Airspace users in fact base their aircraft purchase decisions on detailed quantitative mission-performance data that are for all intents and purposes comparable across aircraft products. Even a modern consumer would typically not purchase an automobile without consideration of objective performance data such as fuel efficiency. However, for ATM TP capabilities, we seem to be limited to anecdotal data, most of which are for operational conditions that are not documented in the detail necessary to be comparable across DST applications. It is often difficult to determine if differences in the accuracy of predicted trajectories are due to the underlying Trajectory Predictor or the quality of the basic flight data input.[5] Even when some data are available, it is not clear if these performances differences are valid for the same conditions. Perhaps the differences in performances are due to differences in operating conditions tested. Many opinions exist across our community, but few if any are backed by objective cross-comparable data in the literature.

To mitigate these problems we propose to complement our community's top-down system design approach (i.e., from ATM concept development down to Decision Support Tool design) with a bottom-up understanding of TP performance. A combined approach: top-down for concept development and tool design on the one hand, and, the bottom-up method for defining the achievable performance of Trajectory Prediction functions on the other hand, creates key opportunities. These opportunities include the ability to seek the necessary compromises between the TP requirements of future DSTs and the TP performance that is achievable within a given time frame and operational context.

The way forward: the 9-point action plan

To facilitate a comprehensive and objective bottom-up approach to TP development and validation, we propose the following nine-point action plan.

Action points 1and 2 will warm up and facilitate community collaboration by defining a common set of terms (to address the confusion of past technical interchanges) and generating a cross-comparable set of TP requirements for the DST projects of interest within the US and European communities.

Action point 3 addresses a common problem shared by all ATSPs having to do with the preparation of airspace adaptation data to support trajectory prediction applications.

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[10] FAA/Eurocontrol Action Plan 6 Report on the Trajectory Prediction Technical Interchange Meeting, February 2003, Brussels, [www.eurocontrol.int/faa-euro]

Action point 4 provides for a comprehensive sensitivity analysis of all the factors that may impact trajectory-prediction accuracy for current and future DST applications.

Action point 5 provides for an objective assessment of aircraft performance modelling approaches and the conditions for which each approach may excel.

Action point 6 addresses a second common problems shared by all ATSPs having to do with the challenges of obtaining and maintaining a quality database of aircraft performance models.

Together, action items 7-9 will tell us which TP errors are likely to occur in ATM operations, the frequency and conditions for which those errors occur, and the data mining of what states can be used to predict these errors in current and future DST applications.

1. *Common TP-Related Terminology*

Agree on the use of common terms and get a common understanding of the components that Trajectory Prediction functions consist of and the Services that they need to provide.

Rationale:
- Our experience from the US/Europe Technical Interchange Meeting (TIM)[6] revealed a good deal of confusion between researchers and organizations when, in many cases, the same term was used for very different meanings. Therefore, a common set of terms and understanding is essential for the specification of the architecture and performance characteristics of Trajectory Predictors and the transfer of technical information between cooperating partners.

Approach:
- A glossary of common terms can be established through a small scale drafting group and updated/maintained as a part of technical interactions.

2. *TP Requirements Survey*

Survey and document the current and future DST requirements for TP functionality.

Rationale:
- It is essential to establish the ability to trace the requirements that Decision Support Tools have for TP functionality and performance against the performance of the supporting Trajectory Predictor and the quality of the basic Flight Data available.
- This activity provides TP requirements that are comparable across the spectrum of ATM concepts/DSTs of interest to the community. The community will benefit from the identification of the intersection and union of TP requirements. The intersection of TP requirements will point to opportunities for leveraging common TP capabilities across DSTs.

Approach:
- The existing report[11] on Trajectory Modelling compiled by NASA-Ames and CAASD constitutes a good basis to initiate this task. The approach will be to extend this work to cover all relevant European and US DST applications.
- Activities will be coordinated and results shared through workshops/TIMs and technical publications.

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[11] Ames/CAASD Common Trajectory Modelling Workshop report, December 1999.

3. ***Proposed Requirements for the encoding in LOA/SOP-defined ATC Constraints***

Revisit existing international standards and recommended practices that support the automatic processing of airspace adaptation data and develop proposed missing requirements for the support of Trajectory Prediction. Examples include ATC constraints defined in Letters Of Agreement" (LOA) and Standard Operating Procedures (SOPs).

Rationale:
- The information contained in LoAs and SOP definitions defines to a large extent the ATM constraints that trajectories may have to conform to. The ability to automatic process these adaptation data in support of the Trajectory Prediction function is paramount to reduce the significant burden of manual adaptation by ATSPs and the resulting potential for error.

Approach:
- This activity is a natural international version of a similar critical item identified by previous NASA/CAASD workshops, and can build on prior work performed by CAASD to develop standards to translate LOA/SOP constraints.[12],[13] This task may involve the appropriate standardization bodies. Standardisation of availability, contents and formats similar to e.g., ARINC 424 definitions for RNAV routes, seems a potentially viable way forward.

4. ***Comprehensive Sensitivity Analysis of TP Factors***

This activity will comprehensively analyse the impact of all physical characteristics upon which TP accuracy will depend (e.g., the fidelity of modelling a turn as either instantaneous, curvilinear, or a full dynamic turn model). The goal is to identify those operational conditions in particular that excite (i.e., lead to) significant trajectory prediction errors.

Rationale:
- The results of this activity will enable TP designers to identify and objectively prioritise those factors that can best improve the TP performance for their specific DST application.
- Results will also enable each stakeholder to estimate the minimum accuracy of their specific TP systems even before they are built.

Approach:
- This activity will leverage prior work performed in Europe and in the US on the sensitivity of trajectory prediction accuracy. Prior work will be reviewed and results compared as a function of condition to identify gaps in the conditions studied (i.e., the environmental situations that models must operate in).
- Perform additional analysis to extend results to complete the comprehensive analysis of the sensitivity of trajectory predictions to environmental factors affecting ATM operations.
- Activities will be coordinated and results shared through workshops/TIMs and technical publications.

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[12] Broste, N., Murray, K., Schwarz, R., Toma, N., August 2001, "Automation Concept for Letters of Agreement (LoAs) and Standard Operating Procedures (SoPs)," WN 01W48, The MITRE Corporation, McLean, VA.

[13] Broste, N., Schwarz, R., Tarakan, R., July 2002, "Automation Concept for Letters of Agreement (LoAs) and Standard Operating Procedures (SoPs)," WN 01W48, The MITRE Corporation, McLean, VA.

5. *Performance-Modelling Approach Evaluation*

Provide an objective evaluation between differing kinetic (force based) and kinematic (parametric) techniques for aircraft performance modelling. This evaluation would apply a generic approach to assess alternative modelling techniques.

Rationale:
- Many critical TP design aspects vary with the aircraft performance modelling technique and approach used. These TP design aspects, among others, include: input data requirements, the sensitivity to input data uncertainty, the fidelity and completeness of the performance model, the computation speed, the effort required to generate the aircraft model, the effort to maintain model and the effort to adapt/extend the model to meet future requirements.

- The results of this activity will facilitate an informed choice of performance-modelling approach for each DST application. This standardized set of objective data (independent of application) will allow stakeholders to cross compare the advantages and disadvantages of alternative performance-modelling approaches for their needs. For example, these results will help stakeholders to identify the modelling approach that provides the best balance between their TP performance needs (e.g., accuracy and speed) and cost (i.e., to develop and maintain over time aircraft-performance models to support DST operations).

- In case it is desired by an ATSP to move toward a single, possibly "hybrid" model (to support multiple ATM applications), the results of this activity would facilitate such harmonisation.

- The results will also provide a technical foundation for addressing the technical aspects of the following action (#6).

Approach:
- This activity will leverage upon current European and US tools and expertise for performance modelling analysis. Current tools provide a foundation upon which several modest enhancements will be needed to facilitate the analysis.

- An initial workshop will be conducted to establish the scope and study requirements as well as requirements to ensure cross-comparable data results. Periodic reviews will be conducted to share results and coordinate progress in future steps.

- All care will be taken to ensure objectivity. For example, all interested parties will be encouraged to include evaluation criteria while none will be excluded.

6. *Requirements for Aircraft Performance Data*

Propose a consistent set of requirements for the specification of aircraft performance data that are needed from the aircraft manufacturers to drive the performance modellisation process. This task may involve the appropriate standardization bodies.

Rationale:
- The community cost of having each ATSP independently coordinate and address these issues with each aircraft/FMS manufacturer would be grossly inefficient if not prohibitive. A standardized community approach would result in significant resource savings for both ATSPs and manufacturers.

- A community approach to this set of issues would also expedite the completion of agreements between the ATSP and manufacturer communities. Prior to any industry-wide precedent, it could potentially take several years to develop

acceptable terms for agreement, particularly if each stakeholder must negotiate the terms separately.

Approach:

- A series of workshops will be conducted, as needed, to establish the process and define needs with consideration for the progress from action #5. This activity will leverage prior actions such as those performed by the Eurocontrol Experimental Centre.[14] It is assumed here, that any issues related to intellectual property rights of the manufacturers will have been addressed by the appropriate entities.

7. ***Comprehensive TP Validation Reference Data Set***

Design, collect, analyse and characterise a superset of reference trajectories and associated data for the purpose of the validation of current and future TP applications. The characterization shall include an explicit description of the environmental conditions encountered (or modelled) by the reference trajectory.

Rationale:

- This task will create a common US/Europe Trajectory Prediction Validation database comprised of reference trajectories and related TP performance metrics. These data will provide stakeholders with a broad, generic, and common set of reference information for evaluating the performance of their specific Trajectory Prediction capabilities under known conditions. These reference data will be representative of key operational conditions that are relevant to current and future ATM DST operations.
- Subsequently, this information will provide each DST designer with the data necessary to assess the performance of their TP capabilities under nominal and exceptional conditions. The availability of information of this level is absolutely essential for the safety and performance assessment of an ATM system based on the use of such DSTs.
- Real flight data (vertical and horizontal profiles), sensor recordings, and pilot interactions will facilitate high-fidelity validation (i.e., a "virtual flight test") of current and new TP capabilities.
- A common database will enable ATSPs and stakeholders to cross compare the performance of multiple TP systems against a common set of reference trajectory data of high fidelity and quality.
- The results from this activity will lend themselves to the establishment of standards that will ease the certification process of TP/DST applications.

Approach:

- This activity will involve the collection, analysis, and publication of trajectory validation data (i.e., truth trajectory and relevant conditions). The approach will begin with the collection and organization of existing data to identify key gaps.
  - An initial Workshop/TIM will define the overall scope and study requirements
  - Periodic reviews will be used to coordinate contributions through distributed efforts in the US and Europe
- Studies will be conducted to collect and analyse new data to fill the gaps.

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[14] Eurocontrol Base of Aircraft Data (BADA) license agreement available at www.eurocontrol.fr/projects/bada/license.html

- To minimize costs, and maximize the breadth of reference data, we have identified four complementary analysis approaches:
    - Analysis of Aircraft performance model / flight-planning tool runs (to provide validation data for vertical profiles under controlled "known" conditions)
    - Analysis of Aircraft/FMS simulation runs (to provide a broader set of validation data reflecting lateral navigation and pilot procedures/techniques under controlled conditions)
    - Analysis of actual flights using on-board and radar track data (to provide a sample set of validation trajectories subject to real-world conditions that are measured comprehensively and precisely).
    - Analysis of actual flights using radar track data (to provide the broadest set of validation trajectories subject to real-world conditions, but not all factors are precisely measured)
- The sharing of expertise, local knowledge, cost, etc. will ensure the completeness of the reference data to cover all operational conditions. If performed as a joint project, in principle this task is a one-off work. Future updates of the database are only needed for when ATM or aircraft operating procedures are applied and/or when new categories of aircraft (e.g. A380) are introduced.

8. *Assessment of the Operational Application of ATM Constraints*

Design and conduct an operational assessment of the type and frequency of "ATM constraints" and the conditions under which they are applied or excluded. ATM constraints represent the constraints the ATM system imposes on trajectories such as published crossing restrictions (altitude, speed, and/or spacing at a point), and restrictions that are imposed by controllers (e.g., in response to "letters of agreement" between ATC facilities and sectors). The assessment will organize a statistically significant sampling of typical regions of US and European airspace.

Rationale:

- This activity will provide the community with a quantitative dataset indicating the frequency of ATC constraint activation, and the conditions under which the constraints are activated, for a representative set of sectors. Such data will be critical to the estimation of the impact of actual ATC constraints on TP/DST performance for the airspace and operational conditions of interest to new DST applications. Results will enable stakeholders to compare the performance of multiple TP/DST applications against a standard set of known conditions.
- Knowledge of actual ATC constraint activation will also provide stakeholders with useful data for understanding the contribution of ATC constraint impacts on broader assessments of field data. In other words, by isolating this significant contribution to intent uncertainty, the impact of this source of potential intent error can more easily be isolated from other factors that impact field test data that are subject to a range of other TP-prediction error sources.

Approach:

- Much contributing progress has already been done in the US and Europe. This activity will begin with an assessment and compilation of related results. Gaps will be identified and addressed in the following approach tasks.
- This activity will conduct a comprehensive interview/questionnaire-based operational assessment (many facilities and sectors) that is representative of the US and European ATSP environments.

- This activity will be designed to leverage earlier work[15] that identified types of constraints and their use. This extension will provide quantifiable results indicating the frequency and conditions of constraint activation.

- An in-depth data analysis will be performed on a subset of the sectors/facilities assessed by questionnaire/interview. This activity will analyse a finite set of track and flight plan data to validate the results from the earlier assessment. Actual flight conditions will be compared to controller estimations of frequency and conditions for ATC constraint activation.

- Activities will be coordinated and results shared through workshops/TIMs and technical publications.

9. ***Comprehensive Operational Assessment of Intent Prediction Errors***

Design and conduct a statistically significant operational assessment to determine the distribution of events that can lead to intent errors.[16]

Rationale:

- This assessment will provide the community with the knowledge of the frequency, extent, and conditions causing essentially all significant intent errors that impact the accuracy of TP trajectories supporting DST operations. These data will provide an invaluable resource to each DST stakeholder to virtually test and validate their automation concepts and systems against conditions representing real-world challenges.

- Results will provide ATSPs with an accurate estimate of the impact of real-world intent errors on systems before deployment. This will facilitate more accurate cost-benefit assessments for basing implementation decisions, and it will allow stakeholders to compare alternative DST options to determine which ones will best reduce and/or mitigate trajectory prediction errors dues to intent uncertainty.

- Knowledge of actual distributions and frequency of intent errors will allow stakeholders to focus their efforts and limited validation resources to those cases that would be critical to operational acceptance.

Approach:

- This activity will begin with a comprehensive survey of the literature. In particular, this activity will leverage and extend prior work.[17,18]

- This in-depth data assessment will extend the prior work based on lessons learned and the development/application of more powerful data analysis/mining tools. Such work is time intensive and often requires the synchronized analysis of flight plan and track data, controller-pilot communications (e.g., voice recordings), TFM restriction logs and weather data.

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[15] Post, W., "*A Common ATC Constraints Model for Trajectory Prediction,*" NLR-CR-2001, November, 2001.

[16] Intent errors occur when a controller either issues an instruction, but doesn't update the flight data accordingly, or when the controller intends to issue instructions, but such instructions are not reflected in today's flight data processing. Pilot intent error is another related source of intent error that can impact a trajectory prediction when the pilot is allowed to manoeuvre at their discretion. Examples include undocumented provision of direct routes and flight level changes, the resolution of potential conflicts, the impact of Letters of Agreement, controller interventions for the purpose of metering and spacing, flight profile adaptations to avoid heavy weather, unrecorded tactical events in the air and on the ground, etc.

[17] Lindsay, Kenneth S., January 2000, "Results of a URET Operational Utility Experiment", WN 00W81, The MITRE Corporation, McLean, VA (this work assessed the completeness of the intent information (lateral, vertical, speed) that NAS automation (Host) provided to DST (URET) automation during 9 sector-hours of operations).

[18] Rozen, Nicholas E. and Kenneth S. Lindsay, April 2001, "Functional Performance of the User Request Evaluation Tool (URET) Delivery 3.4 Release 4", MTR 01W31, The MITRE Corporation, McLean, VA (This analysis quantified false and missed alert rates, two key URET performance metrics, as functions of intent information quality. This analysis focused on lateral and speed intent since reference 11 indicated that vertical intent information is fairly complete and accurate).

- Due to the extensive scope and complexity of this task, analysis tools and techniques will be developed collaboratively, and shared, where practicable. This joint approach is needed to achieve the desired results for an acceptable cost.
- Activities will be coordinated and results shared through workshops/TIMs and technical publications.

Together, action items 7-9 will tell us which TP errors are likely to occur in ATM operations, the frequency and conditions for which those errors occur, and the data mining of what states can be used to predict these errors. With this knowledge, the community of DST designers will know precisely what challenges must be addressed to improve the quality of the predicted trajectories in order to achieve their desired DST performance goals. These data will also provide DST designers with the information necessary to determine the value of enhancements to their DST and TP systems. For example, the Downlinking of Aircraft Parameters (DAP) will resolve some TP errors for the portion of traffic so equipped. Other enhancements such as improved ground-based tracking, wind prediction, intent inferencing, and active advisories will reduce TP errors as well. A comprehensive, DST-application-independent database will help designers estimate the relative impact of each enhancement individually, and/or in combination. This will enable each designer to make objective cost-benefit tradeoffs between alternative and complementary approaches for enhancing their DST.

Conclusions

This document has identified a set of common trajectory prediction R&D issues and has detailed a nine-point program to address them. The items described in this program are independent of the specific trajectory prediction software evaluated and the results will not be limited to a specific operational environment. Adoption and execution of the proposed action plan will:

- Identify the main issues that we face in the development of trajectory predictors,

- Assess and leverage prior work across the community, avoid duplication of effort, and merge expertise in the many organisations involved in tool and predictor development to the advantage of the community,

- Deliver a common methodology and resources to support the validation and improvement of trajectory prediction capabilities. The resources will be independent of particular concepts and DSTs. Resulting data sets and analysis tools will be designed for reuse by the entire community, rather than by just one organisation. US-European collaboration will result in a comprehensive set of resources (including the test environment, input data, analysis tools, and results) that will enhance the quality of the validation and improvement process. A further consequence of the use of common data will be validation results that are cross-comparable,

- Contribute to the development of standards to reduce costs associated with the development, maintenance, and interoperability of TP capabilities,

- Facilitate the development of comprehensive trajectory predictor requirements.

If executed, this cross-cutting DST platform-independent plan will accelerate progress in the research and development of trajectory prediction, reduce the cost, schedule, and risk of implementing future DSTs while maximizing performance and interoperability.

Recommendations

We ask the R&D committee to:

- Sanction the 9-points plan and recommend to the European and US agencies that they seek appropriate resources for the execution of the points described herein.

- Identify the stakeholders that should sponsor and/or participate.

- Recommend how to get stakeholders to sponsor the work, participate, and synchronize with other stakeholders.

- Recommend how to disseminate the results to the community.

Next steps

Upon sanction of this proposed plan of action, the next step will be to develop a Europe/US Research Coordination Plan (RCP) for Trajectory Prediction. This activity will be comprised of three actions:

First, a team shall draft he RCP. This RCP will define the technical details of the work to be performed and present a roadmap for completion (project plan, schedule, roles and responsibilities of supporting organizations). The RCP shall also identify the need for and value of each activity to the sponsoring and stakeholder organisations.

Second, this white paper and draft RCP will be distributed to the larger community of stakeholders to solicit their review, comment and concurrence.

Third, based on stakeholder feedback, the European and US agencies would then have an opportunity to selectively fund the activities of greatest value and urgency. The results would be subject to review by the cross-cutting technical team (to maximise use/relevance to the community), published in the appropriate literature, and made available to supporting stakeholders.

Acknowledgements

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This white paper could not have reached this level of maturity or community consensus without the active support and insightful participation of the ATM community. In particular, we would like to extend our thanks to our colleagues within many key organizations including Eurocontrol (Experimental Centre and Headquarters), the FAA, NASA, CAASD, and NATS.

Appendix A: Acronyms

ARINC	Aeronautical Radio Incorporated
ATM	Air Traffic Management
ATSP	Air Traffic Service Provider
CAASD	Center for Advanced Aviation System Development
CALM	Computer-assisted Approach and Landing Management system
CDA	Continuous Descent Approach
COMPAS	Computer Oriented Metering, Planning and Advisory System
CORA	Conflict Resolution Advisor
CTAS	Center TRACON Automation System
D2	Direct To
DST	Decision Support Tools
DAP	Down-linked Aircraft Parameters
EDA	En route Descent Advisor
FACTS	Future Area Control Tools Support
LoA	Letter of Agreement
FAST	Final Approach Spacing Tool
MAESTRO	Means to Aid Expedition and Sequencing of Traffic with Research of Optimisation
MTCD	Medium Term Conflict Detection
NASA	National Aeronautics and Space Administration
OEM	Original Equipment Manufacturer
PARR	Problem Analysis Resolution and Ranking
pFAST	Passive Final Approach Spacing Tool
RCP	Research Coordination Plan
R&D	Research and Development
RNAV	Area Navigation
SOP	Standard Operating Procedure
TFM	Traffic Flow management
TIM	US/Europe Technical Interchange Meeting
TMA	Terminal
TP	Trajectory Prediction
UERCOP	US-Europe Research COoperation Plan
URET	User Request Evaluation Tool

Appendix B: Products

Execution of the nine points proposed will result in the following products:

- A glossary of common terms in the area of trajectory prediction.

- A compendium of current TP requirements across current and future DSTs.

- Proposed requirements for standardization of airspace adaptation in support of trajectory requirements.

- Data providing the relationship between input data uncertainty and trajectory prediction accuracy. Data describing the error in trajectory prediction due to the exclusion of certain modelling characteristics. These will allow the identification and ranking of areas for trajectory prediction improvement.

- A toolset/environment that will facilitate the objective assessment of the tradeoffs between differing aircraft performance modelling techniques.

- Assessment of the tradeoffs between differing aircraft performance techniques.

- A common interface to Original Equipment Manufacturers (OEMs) for aircraft performance data.

- Community repository of data and results containing data required for validation of trajectory predictors (trajectories with associated data, type and frequency of ATM constraints, and distribution of events leading to intent errors).

- Common validation approach and environment (shared experience, shared data, common methodology and metrics).

Appendix C: Resources:

Estimated Resources Committed (June 03 – June 04)

Research Organisation	In-house	Travel ($/Euro)	Contract
Eurocontrol	2.5 FTE	20 k	2-3 FTE
FAA	2.5 FTE	20 k	tbd
NASA	1 PTE	10 k	tbd
CAASD	1 PTE	tbd	tbd

FTE = Full Time Equivalent
PTE = Part Time Equivalent
MM = 1 FTE for one month
MY = 1 FTE for one year
TBD = To Be Determined

Estimated Resources Required (for task completion)

These estimates assume an international team of technical experts representing core stakeholders.

Action # 1	*Agree on the use of common terms and get a common understanding of the components that Trajectory Prediction functions consist of and the Services that they need to provide.*
Total effort for the action	**Duration**
1 MM / team member	1 year

Action # 2	*Survey and document the current and future DST requirements for TP functionality.*
Total effort for the action	**Duration**
1 MM / team member	1 year

Action # 3	*Revisit existing international standards and recommended practices that support the automatic processing of airspace adaptation data and develop proposed missing requirements for the support of Trajectory Prediction.*
Total effort for the action	**Duration**
1 MY	TBD

Action # 4	*Comprehensive analysis of the impact of all physical characteristics upon which TP accuracy will depend.*
Total effort for the action	**Duration**
2 MY	1 year

Action # 5	*Provide the necessary tools to facilitate the objective evaluation of differing techniques for aircraft performance modelling and perform this study.*
Total effort for the action	**Duration**
3 MY	TBD

Action # 6	*Propose a consistent set of requirements for the specification of aircraft performance data that are needed from the aircraft manufacturers to drive the performance modellisation process.*
Total effort for the action	**Duration**
0.5 MY	TBD

Action # 7	*Design, collect, analyse and characterise a superset of reference trajectories and associated data for the purpose of the validation of current and future TP applications.*
Total effort for the action	**Duration**
4 MY	TBD

Action # 8	*Design and conduct an operational assessment of the type and frequency of ATM constraints and the conditions under which they are applied or excluded.*
Total effort for the action	**Duration**
4 MY	TBD

Action # 9	*Design and conduct a statistically significant operational assessment to determine the distribution of events that can lead to intent errors.*
Total effort for the action	**Duration**
8 MY	TBD